Protons on Target

Ioanis Kourbanis
MI/Beams

Contents

- Goals.
- Slip Stacking (Experiments and Simulations).
- Beam Loading (Calculations and experiments).
- Other beam dynamic issues.
- Target energy deposition and beam sweeping.
- Future studies and Plans.
- Conclusions.

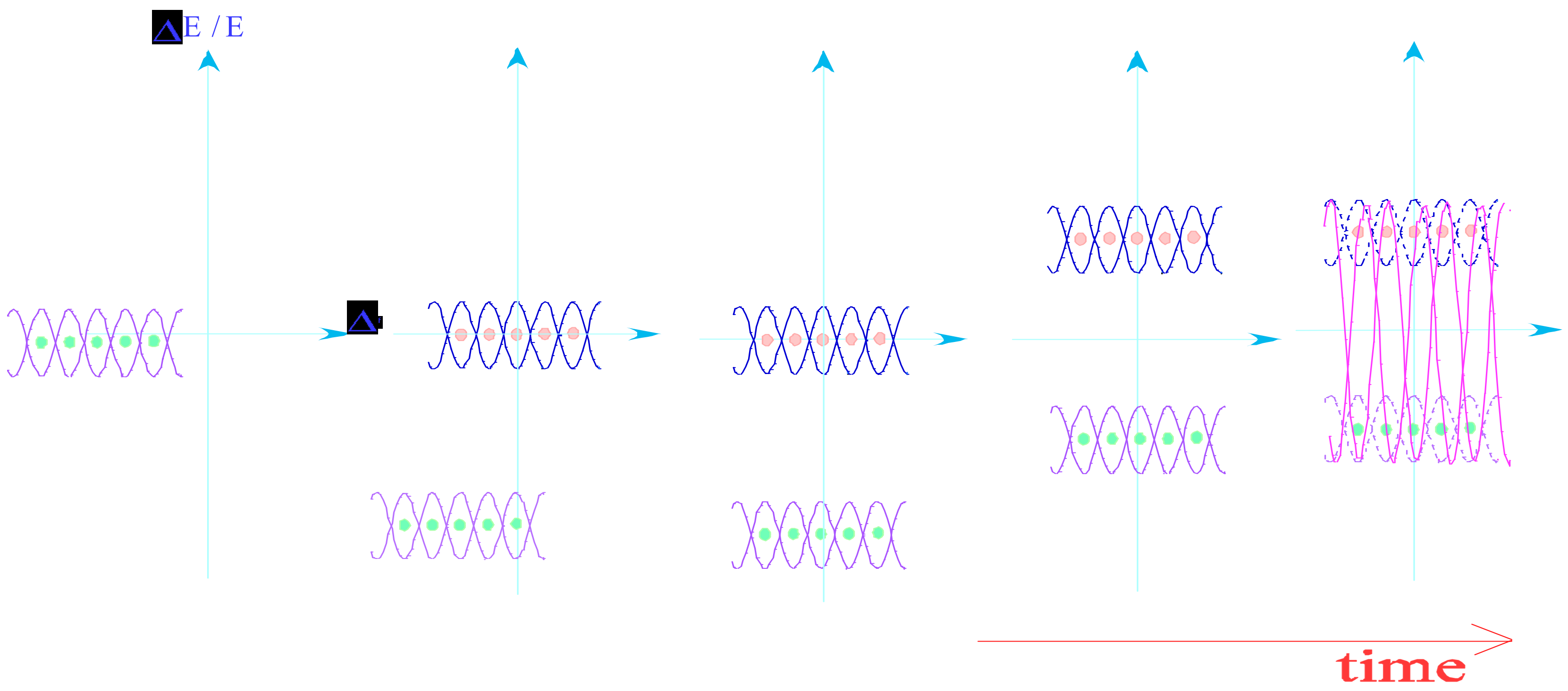
Goals

- Double the beam intensity on the antiproton production target (from 4E12 to 8E12).
- Limit the length of the stacking cycles to 2 sec (including 5 Booster batches for NUMI).
- Produce a bunch length on pbar target smaller than 1.5 nsec.
- Limit the transverse emittances of the beam on target to 25 pi-mm-mrad or less.
- All the above are expected to increase the current stacking rate by a factor of 2.0 (from present).

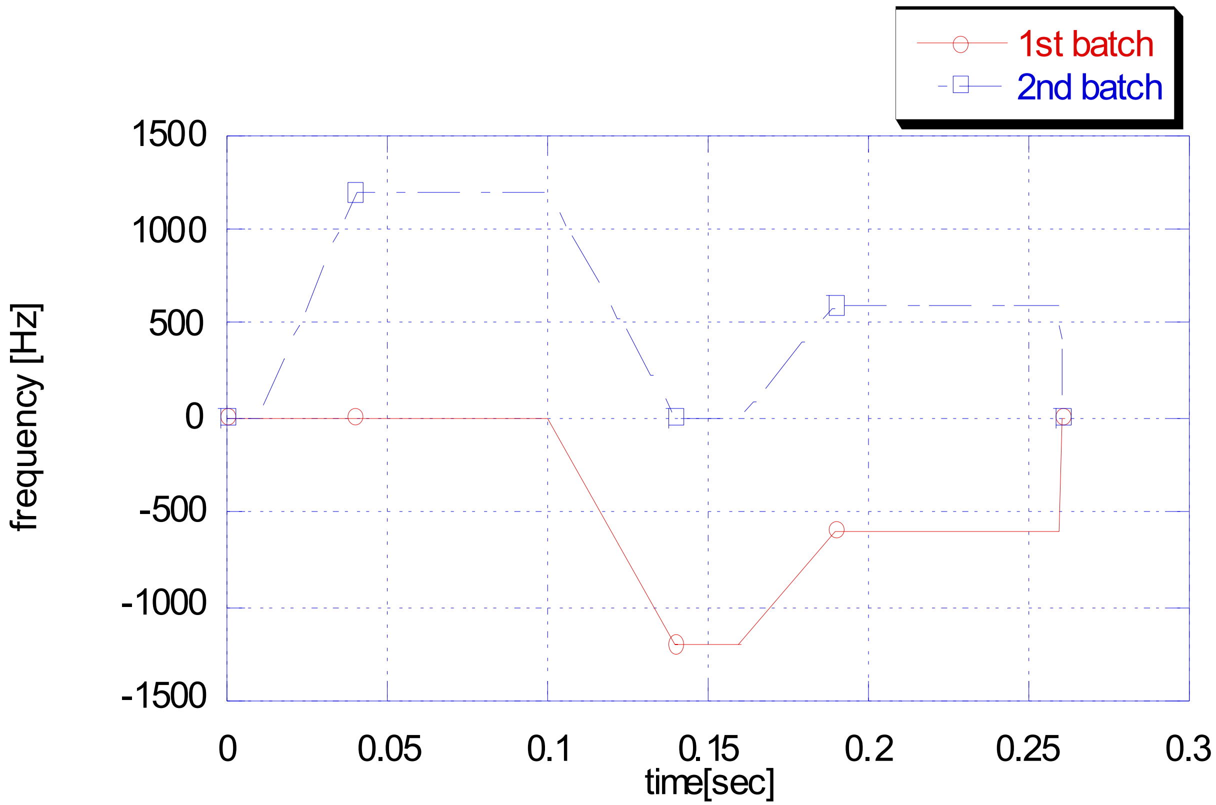
Slip Stacking

- Slip stacking has been demonstrated successfully at low intensities (1.0E12p) in the Main Injector.
- The slip-stacking efficiency was 98% and the final longitudinal emittance blow-up was a factor of 1.6 in agreement with the simulations.
- No longitudinal emittance blow-up has been observed during the slipping of the two batches.
- Most of the LLRF tools needed for slip stacking have been developed.

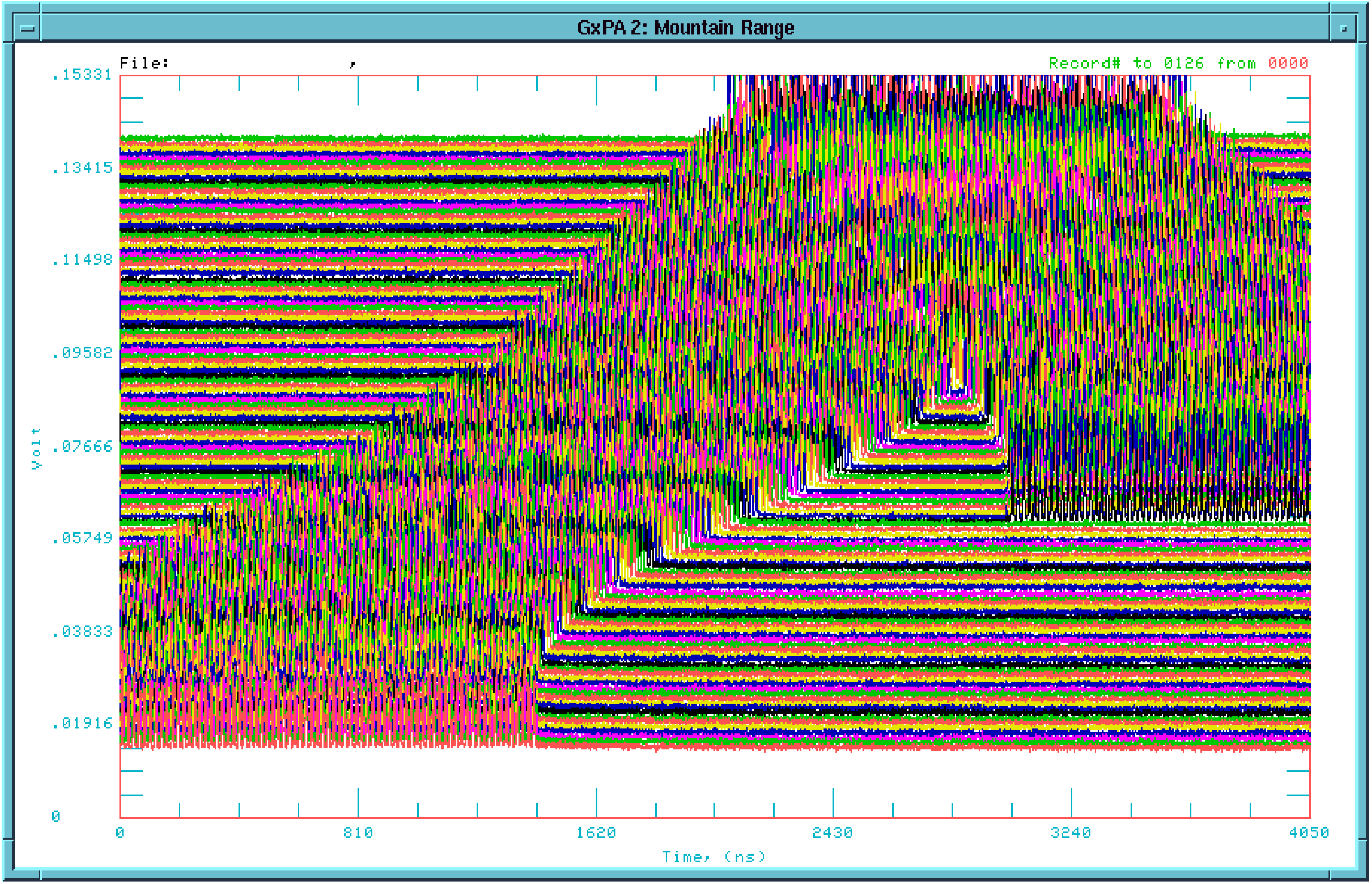
Slip Stacking cartoon



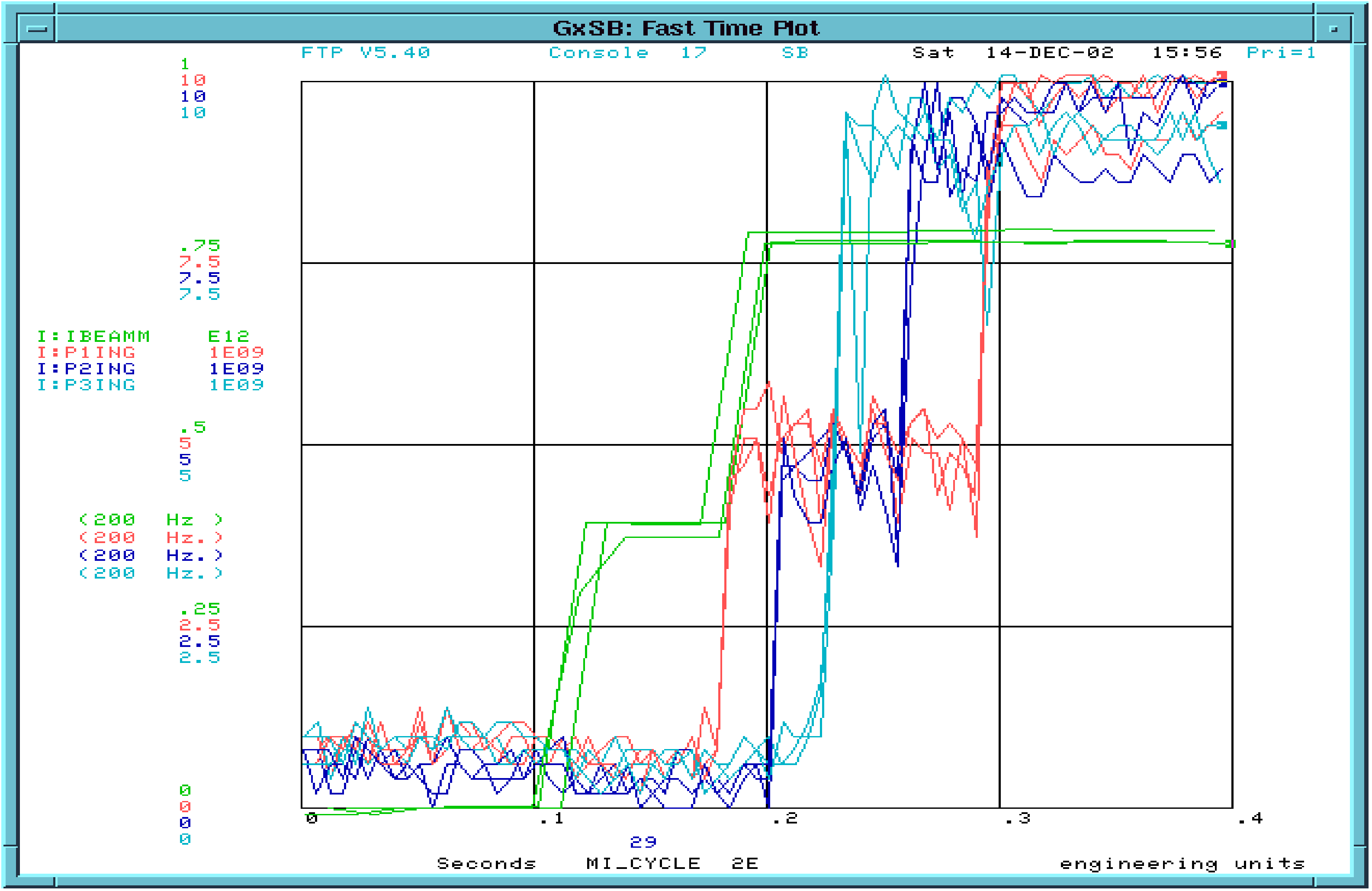
Slip Stacking Frequency Curves



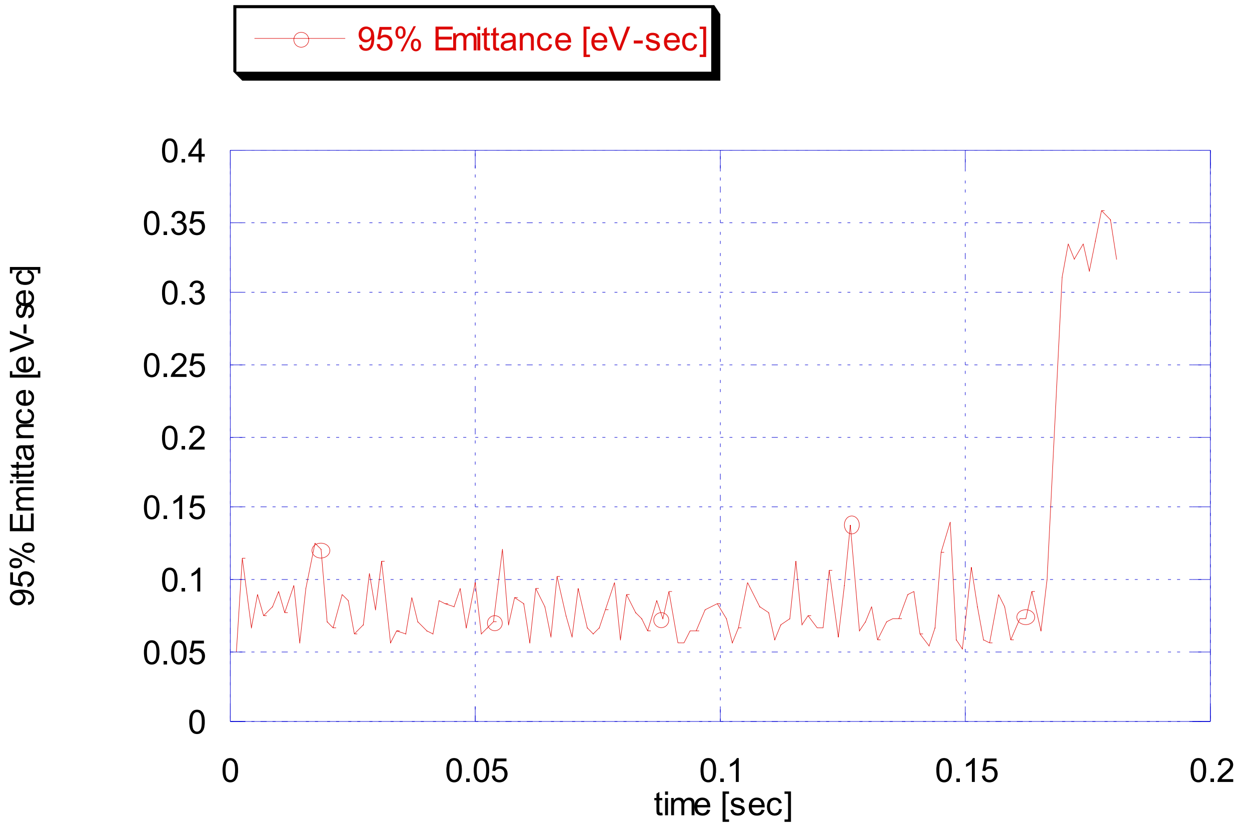
Slip Stacking Mountain Range Plot with 1E12p



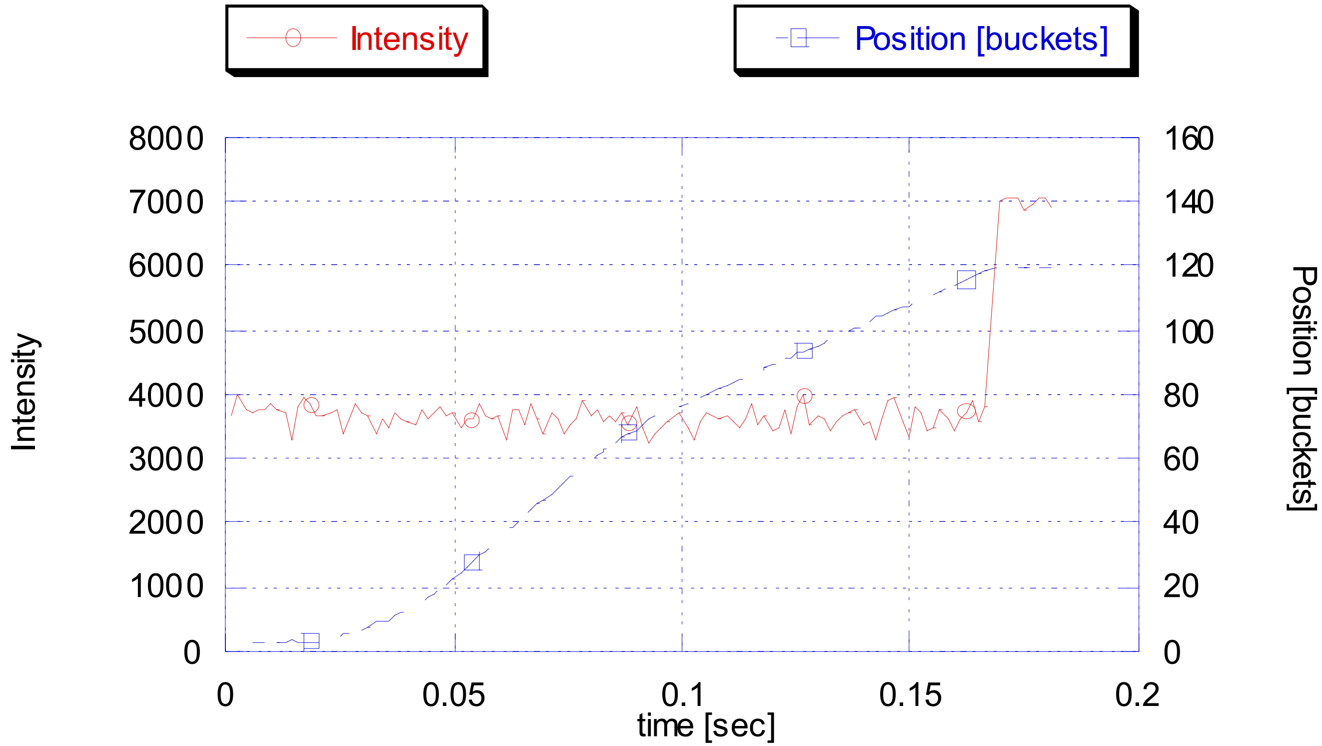
Slip Stacking DC (IBEAMM) and Bunch Beam(P1,3ING) Plots



Longitudinal emittance evolution during the slip stacking Beam Experiment

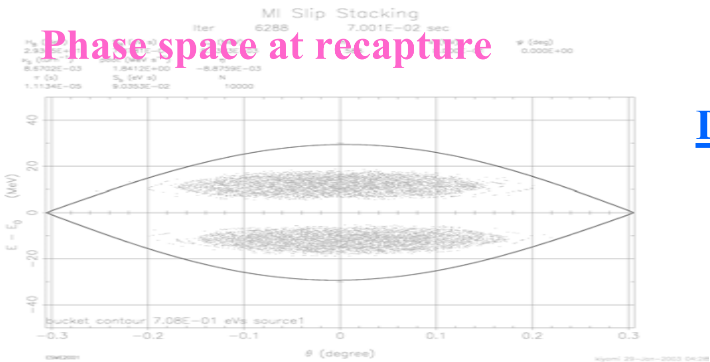


Intensity and position of the first bunch of the first batch during slip stacking

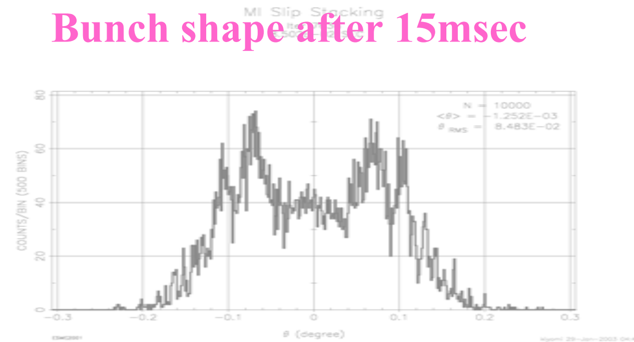


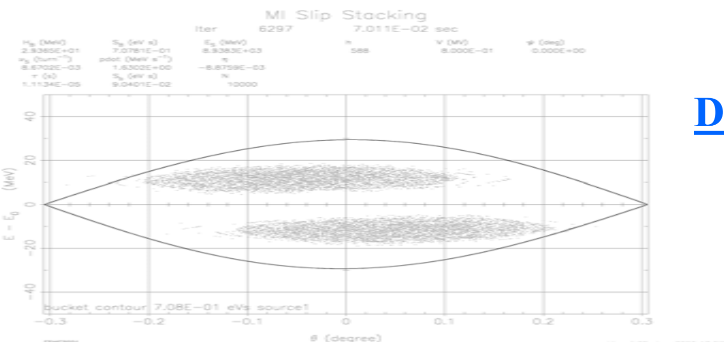
Effect of Recapture time on bunch emittance (simulations)

Phase space at recapture | **Bunch shape after 15msec**

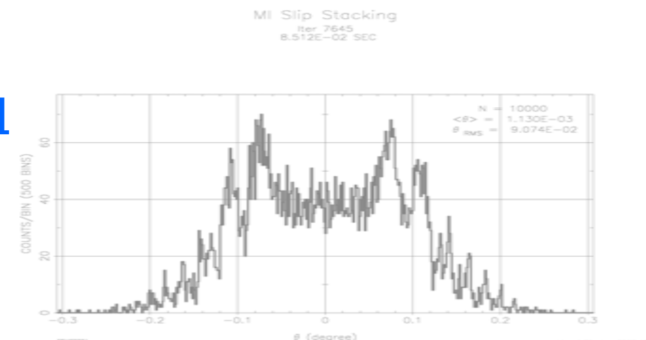


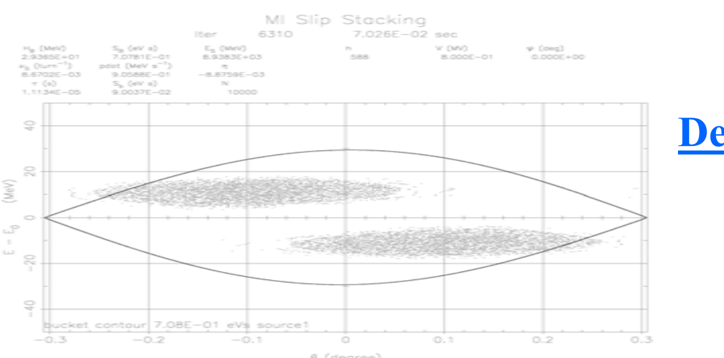
Delay = 0[sec]



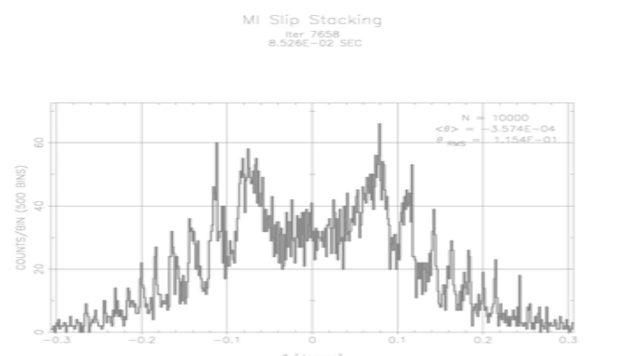


Delay = 100[μsec]

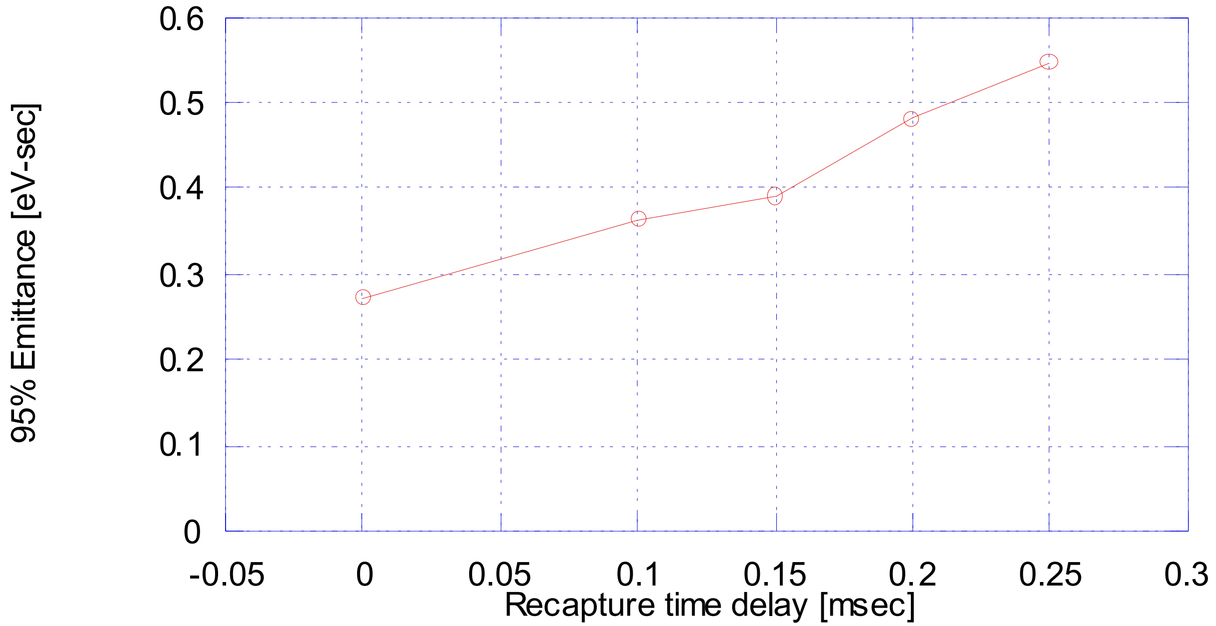




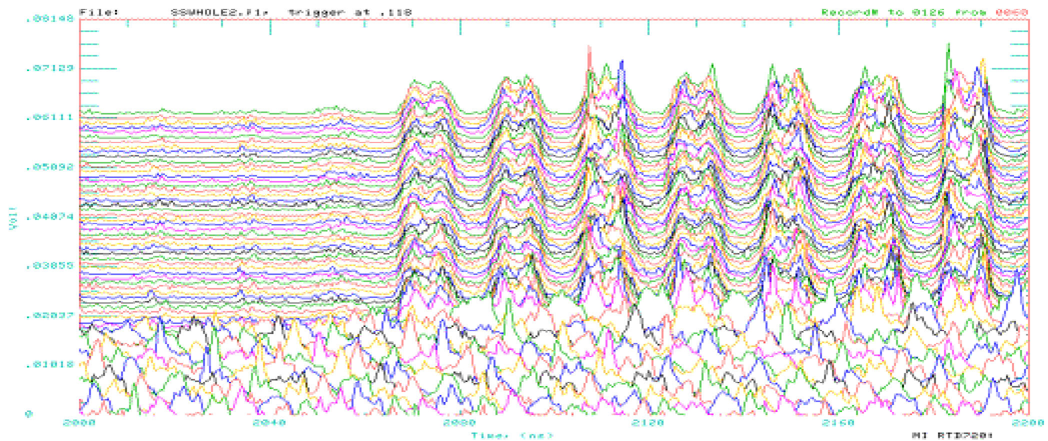
Delay = 250[μsec]

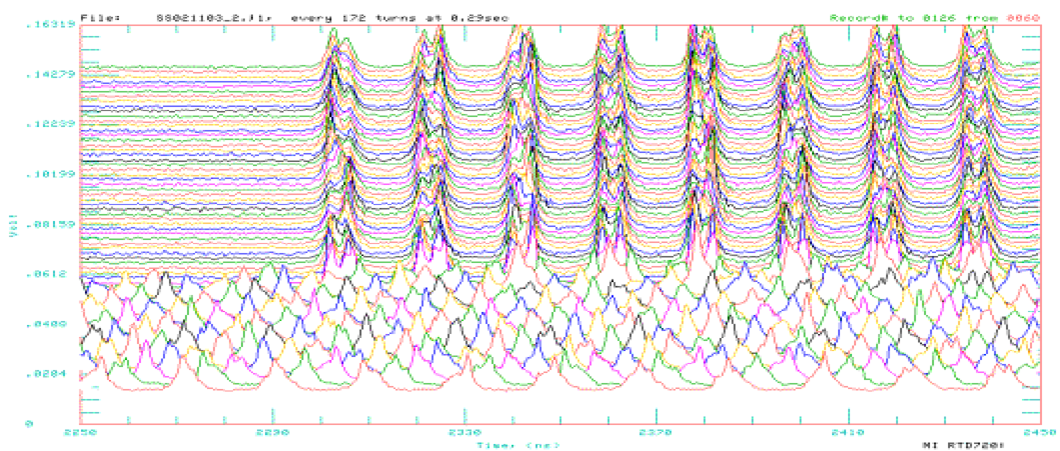


Recaptured beam emittance vs. recaptured time delay (simulations)

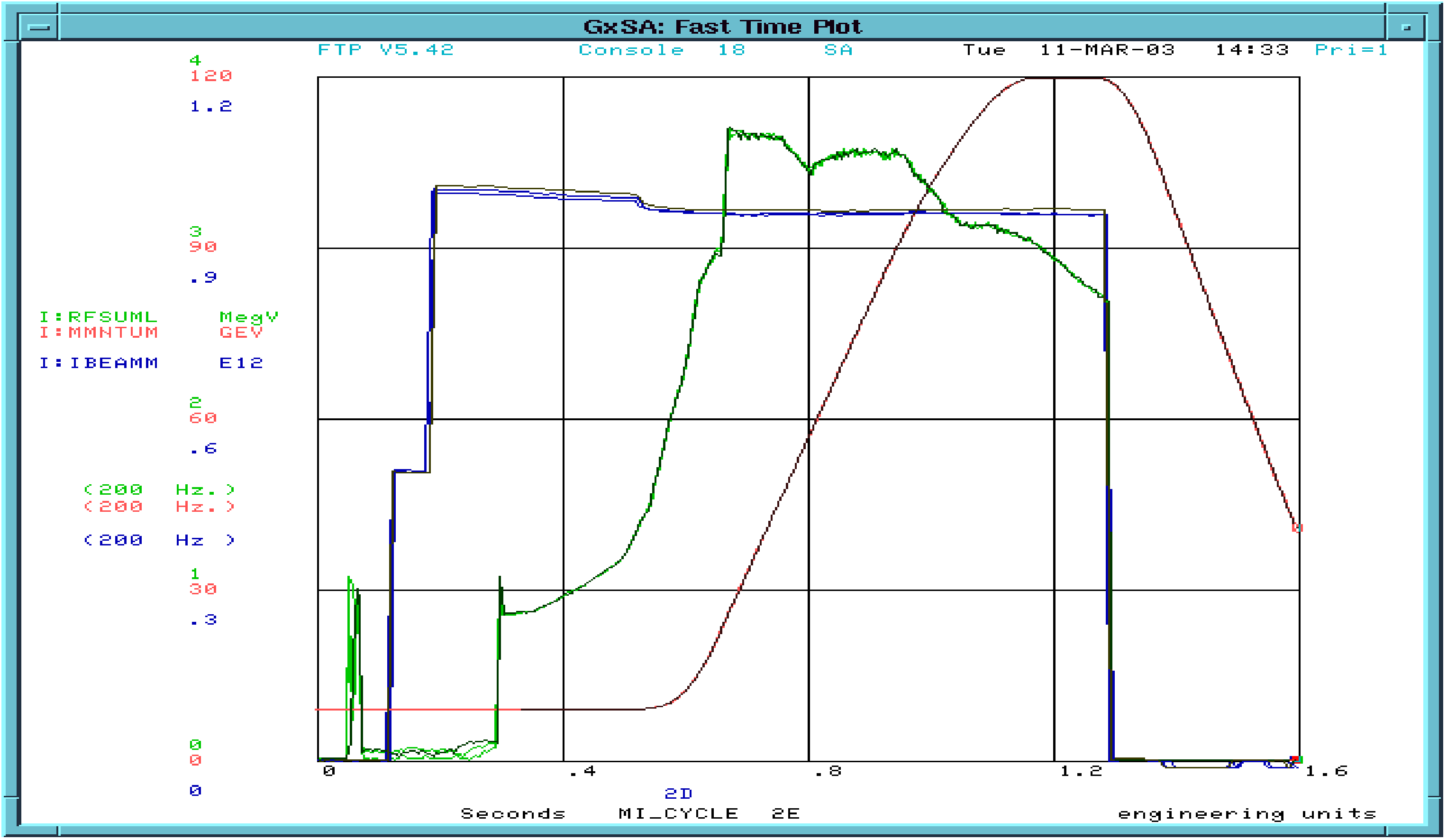


Mountain range plots of slip stacking at recapture time





Acceleration to 120 GeV after slip stacking



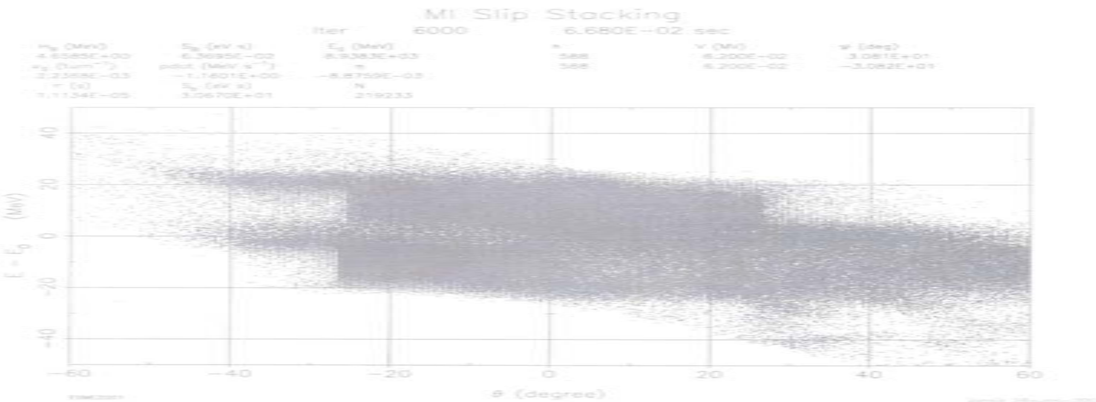
Beam Loading Compensation

- Beam loading on the 53 MHz accelerating cavities is the biggest problem during slip stacking.
- From ESME simulations is determined that at least a factor of 20 (26 db) reduction of the beam loading voltage is required.
- If we use only rf feed-back is used then a gain of more than 100 (40db) is required.
- We can achieve the beam loading compensation using a combination of feed-forward and feed-back.
- We are using a tube performance calculator in Matlab to analyze the performance of the Eimac Y567 cavity tetrodes tubes.
- We have developed a Matlab Simulink model to help us analyze the dynamic behavior of a single MI RF system with its control loops and beam-loading compensation loops.

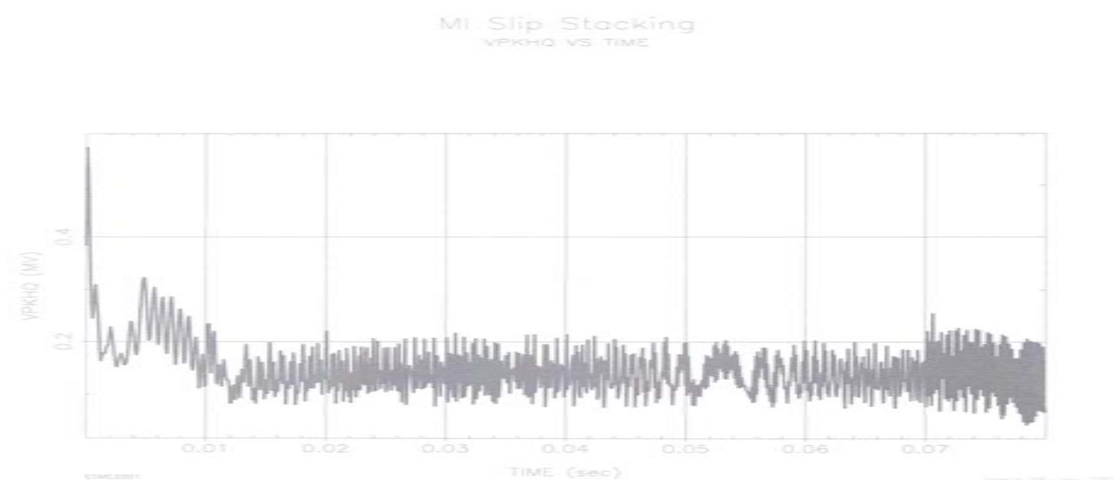
Beam Loading Compensation (2)

- We are currently applying feed-forward compensation with a gain of 20-25db during both proton and pbar coalescing (total beam intensities of 4E11 or less).
- The amount of feed-forward beam loading compensation that we were able to achieve during injection on the stacking cycles with total intensity of 4.2E12 was only 8 db (a factor of 2.5 reduction).
- By changing the operation point of the final tube from class C to class A in one rf station we were able we were able to achieve a total feed-forward compensation of 22 db (a factor of 12.6 reduction).
- We have determined that currently we have enough rf current available to supply the beam-loading compensation required for slip stacking up to intensities of 8E12 p.
- Additional solid state amplifier modules will be needed in order slip stacking to become operational.

ESME Simulations of slip stacking with 1E13p and no Beam Loading Compensation

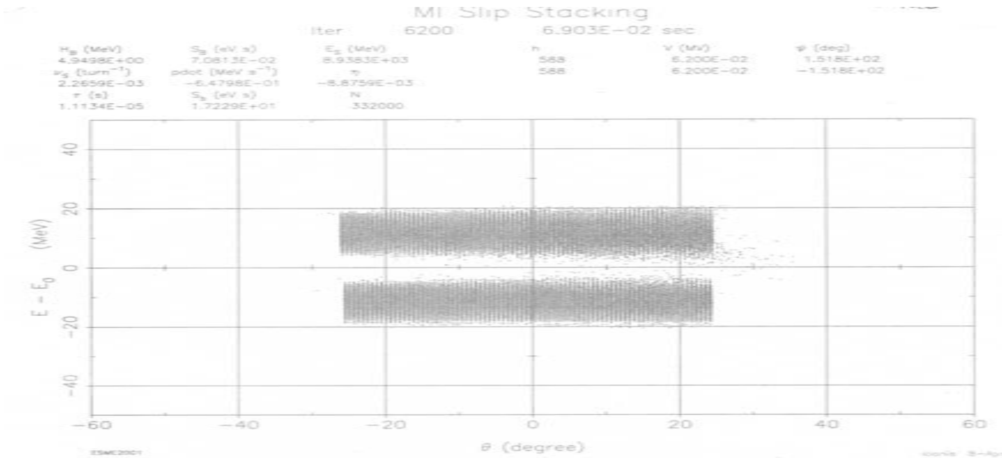


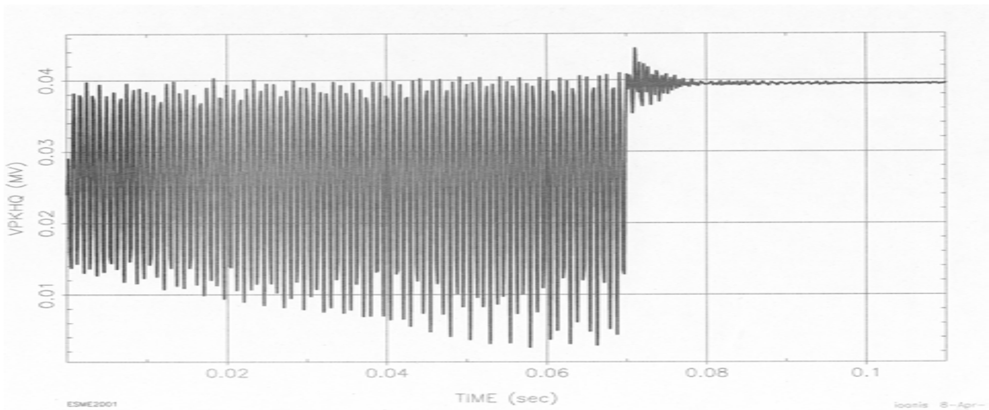
Phase space plot



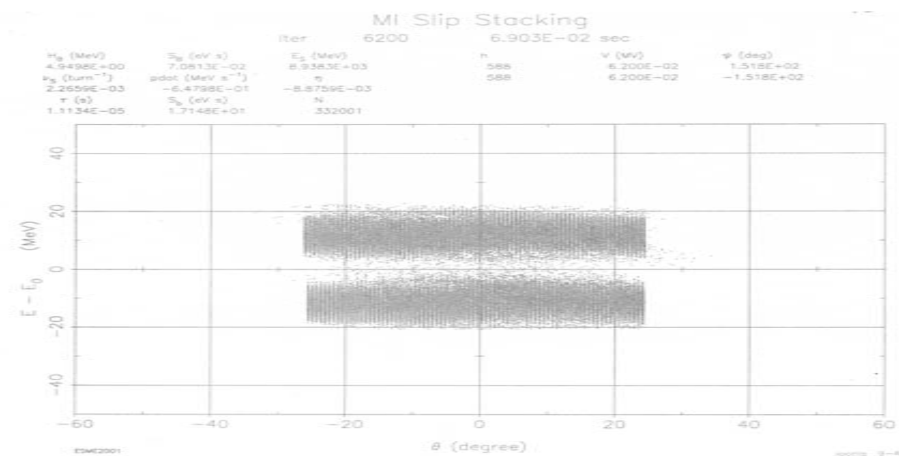
Beam induced voltage

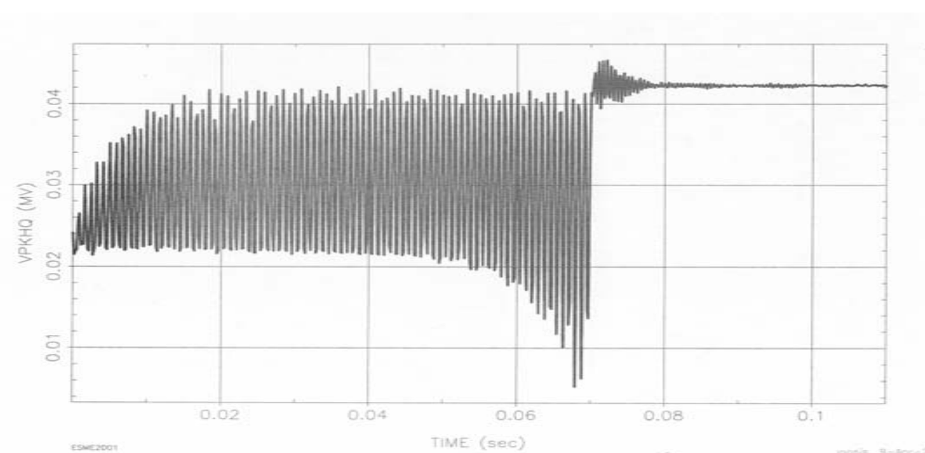
ESME simulations of slip stacking with 26 db of feed-forward compensation



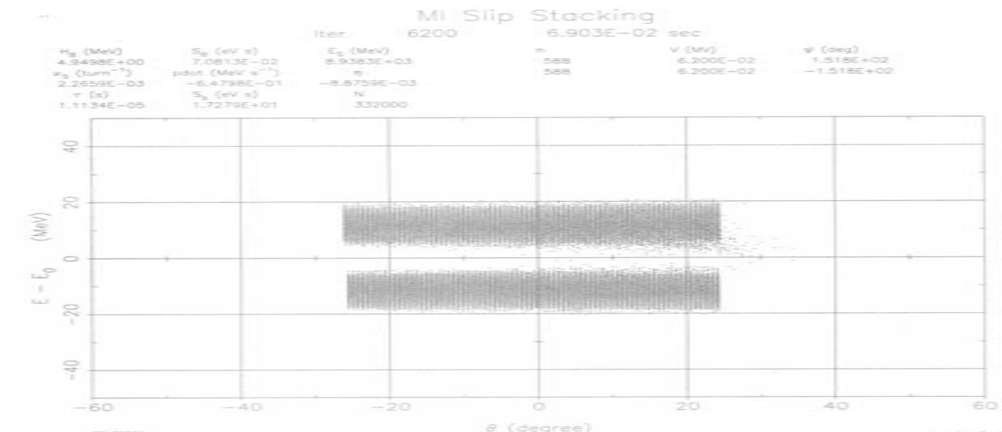


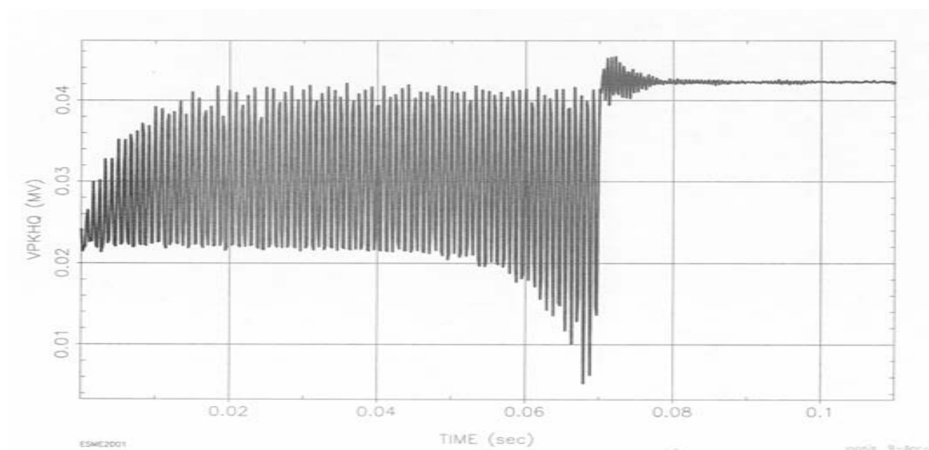
ESME simulations of slip stacking with 40 db of fundamental feed-back



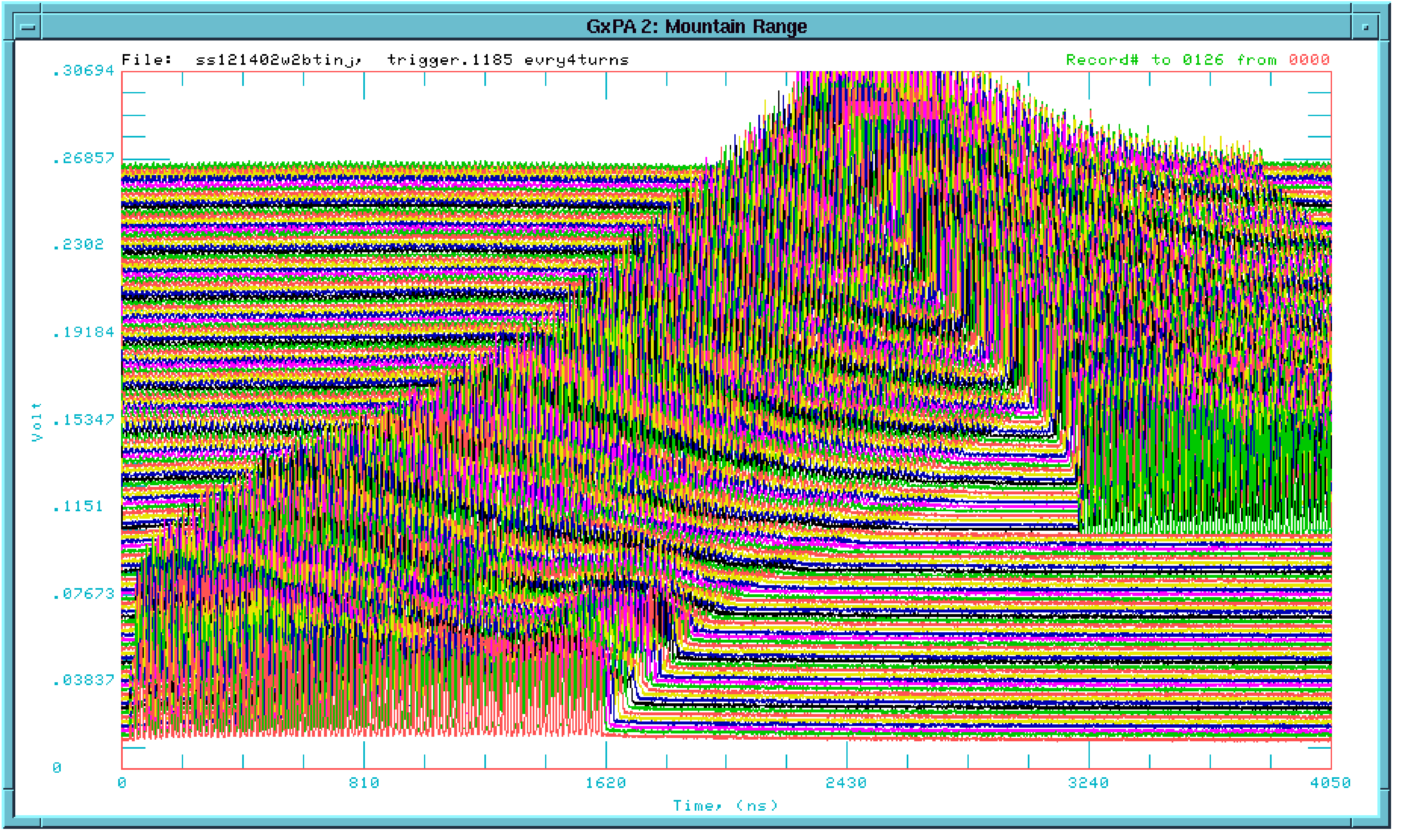


ESME Simulations of slip stacking with 1E13p 20db of feed-forward and 14db of fundamental feedback.

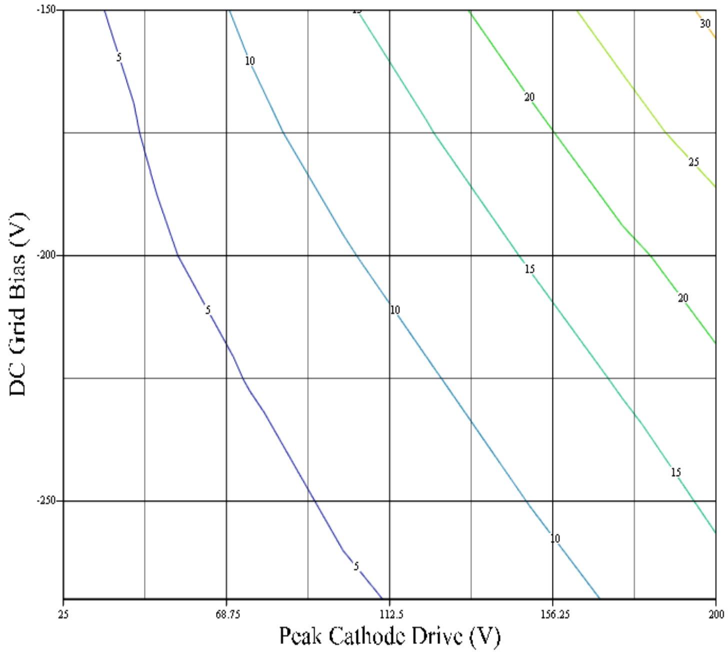


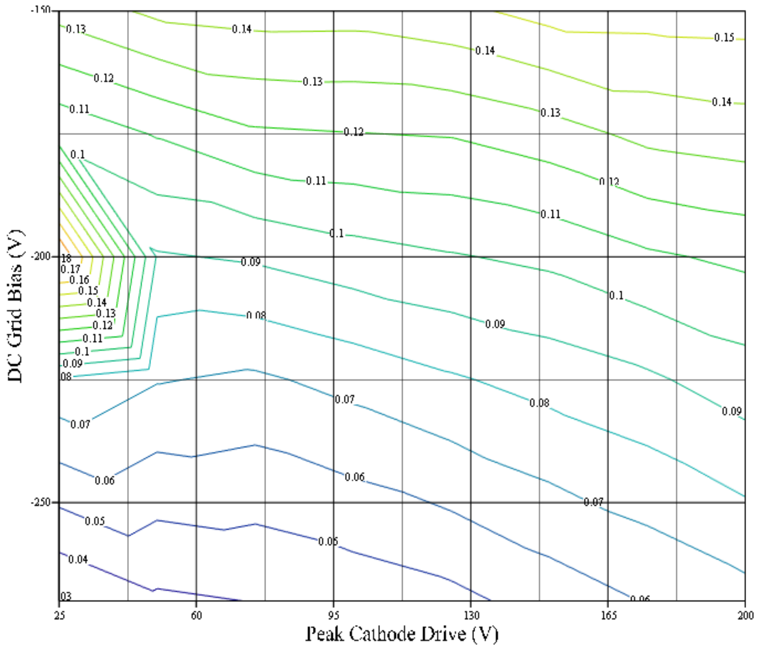


Slip Stacking mountain range with 4.5E12p and no BLC

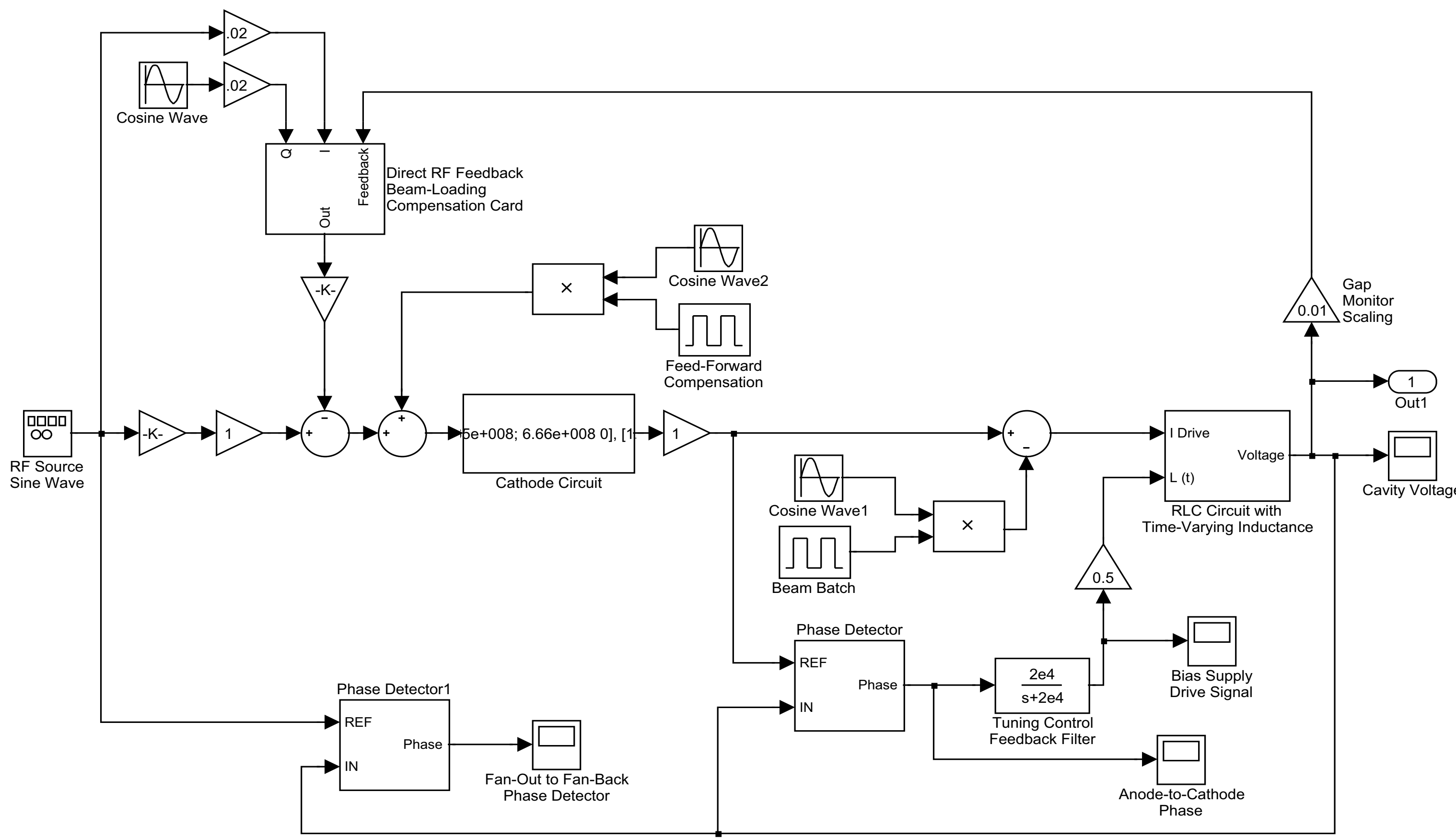


Constant rf anode current and tube transconductance contours as a function of cathode drive and DC grid bias.

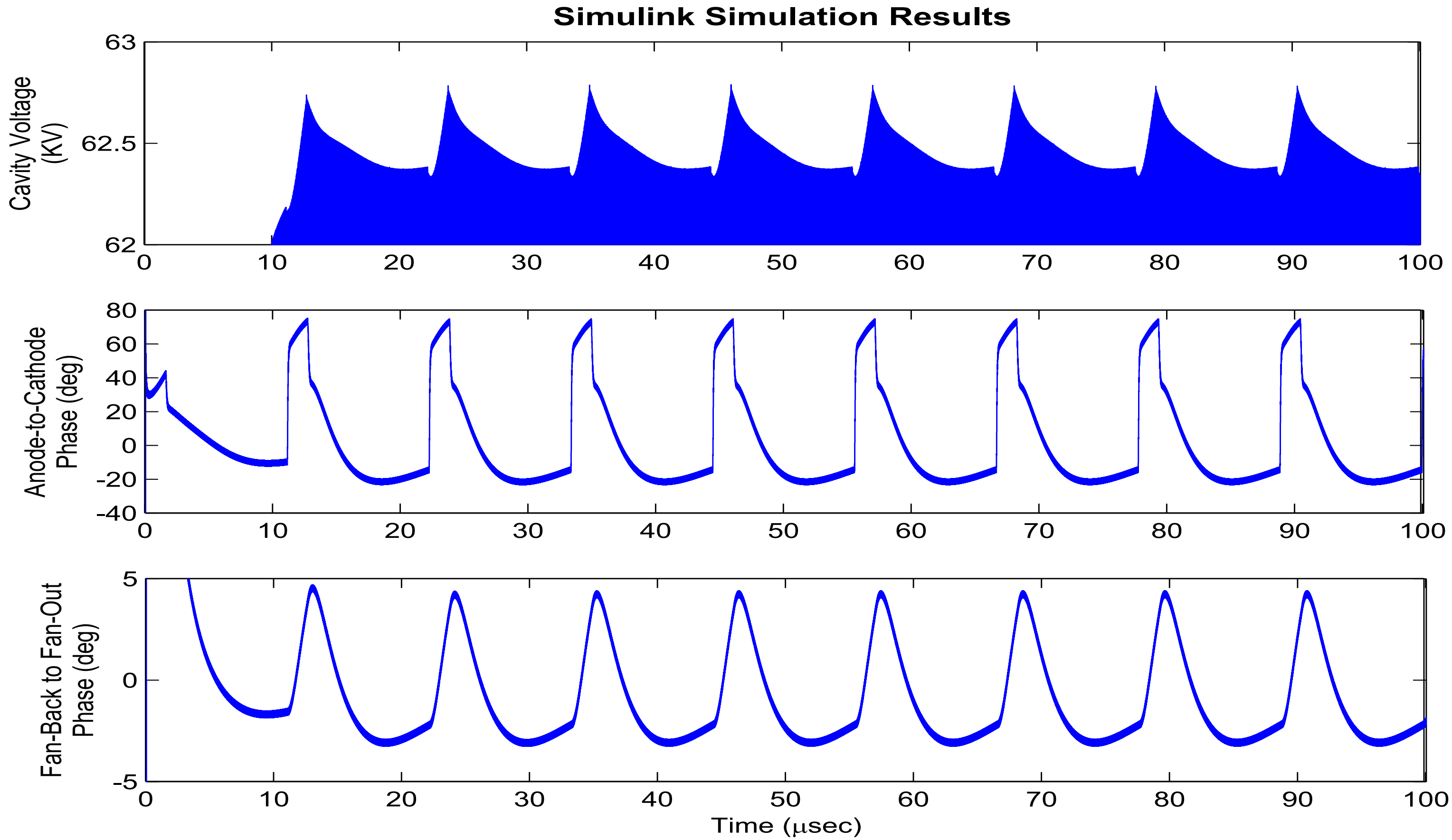




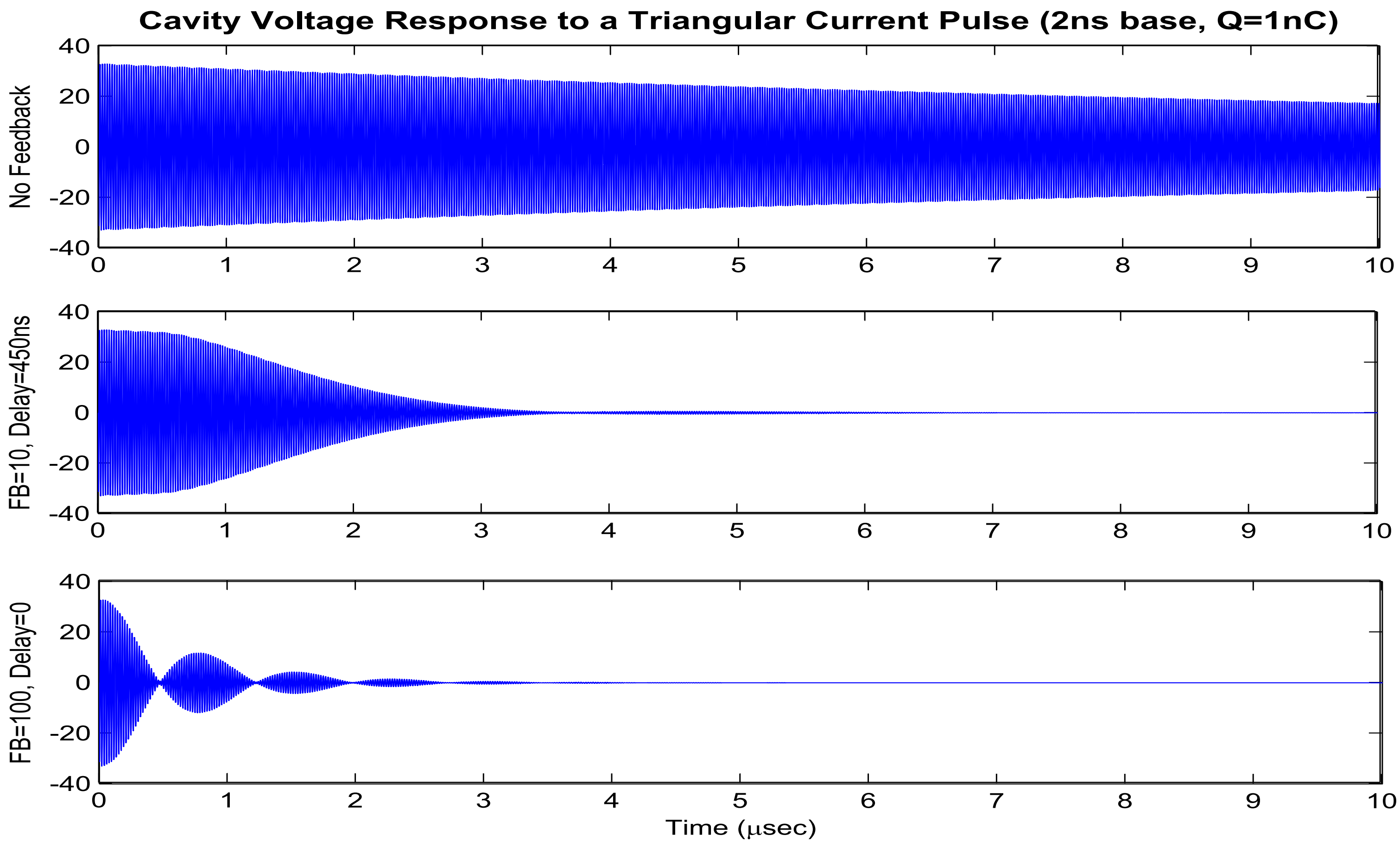
Current Matlab Simulink model of a single MI RF system



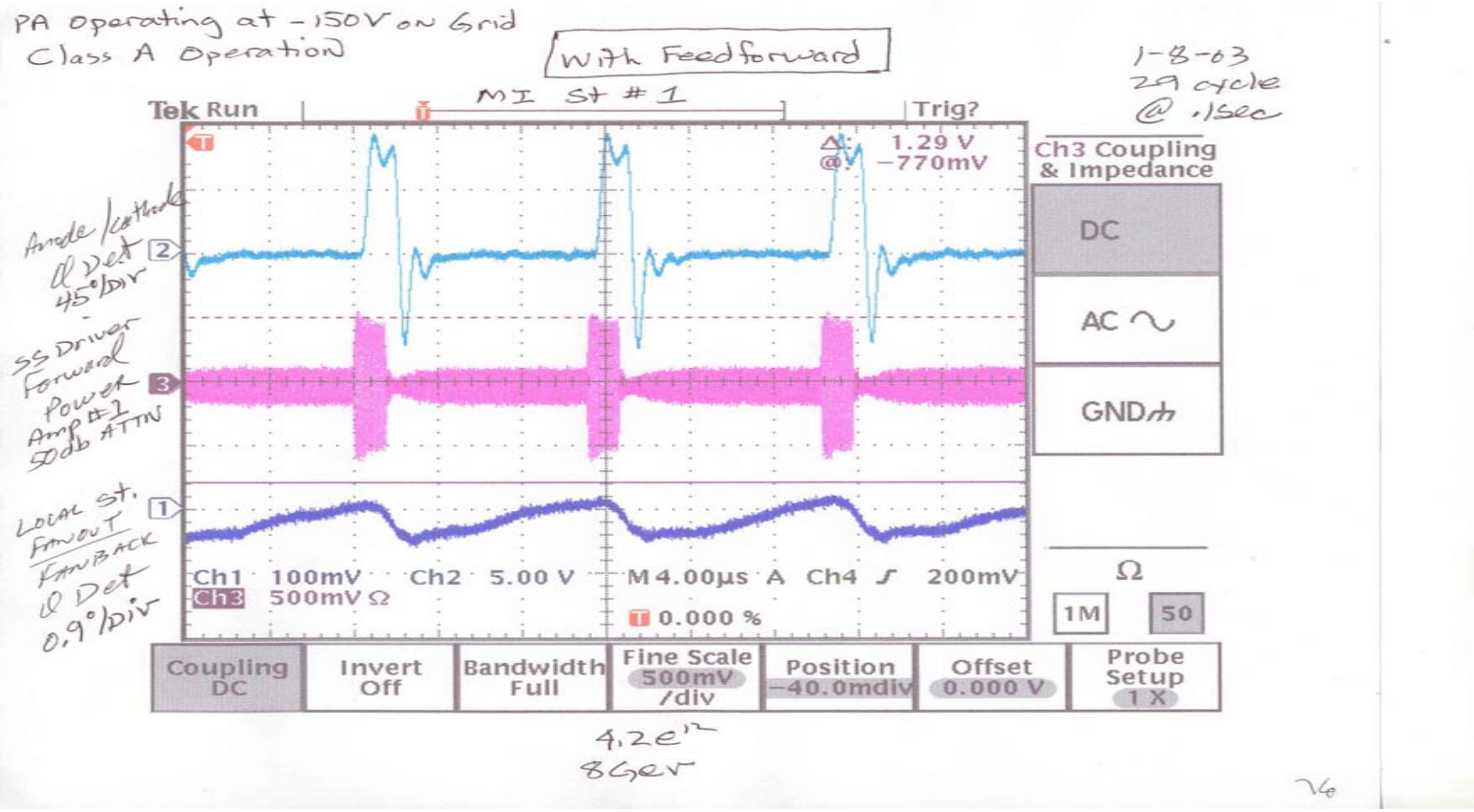
Simulink simulation results (84 bunches, 4E12p, feed-forward with gain of 2, rf feedback with gain of 7).



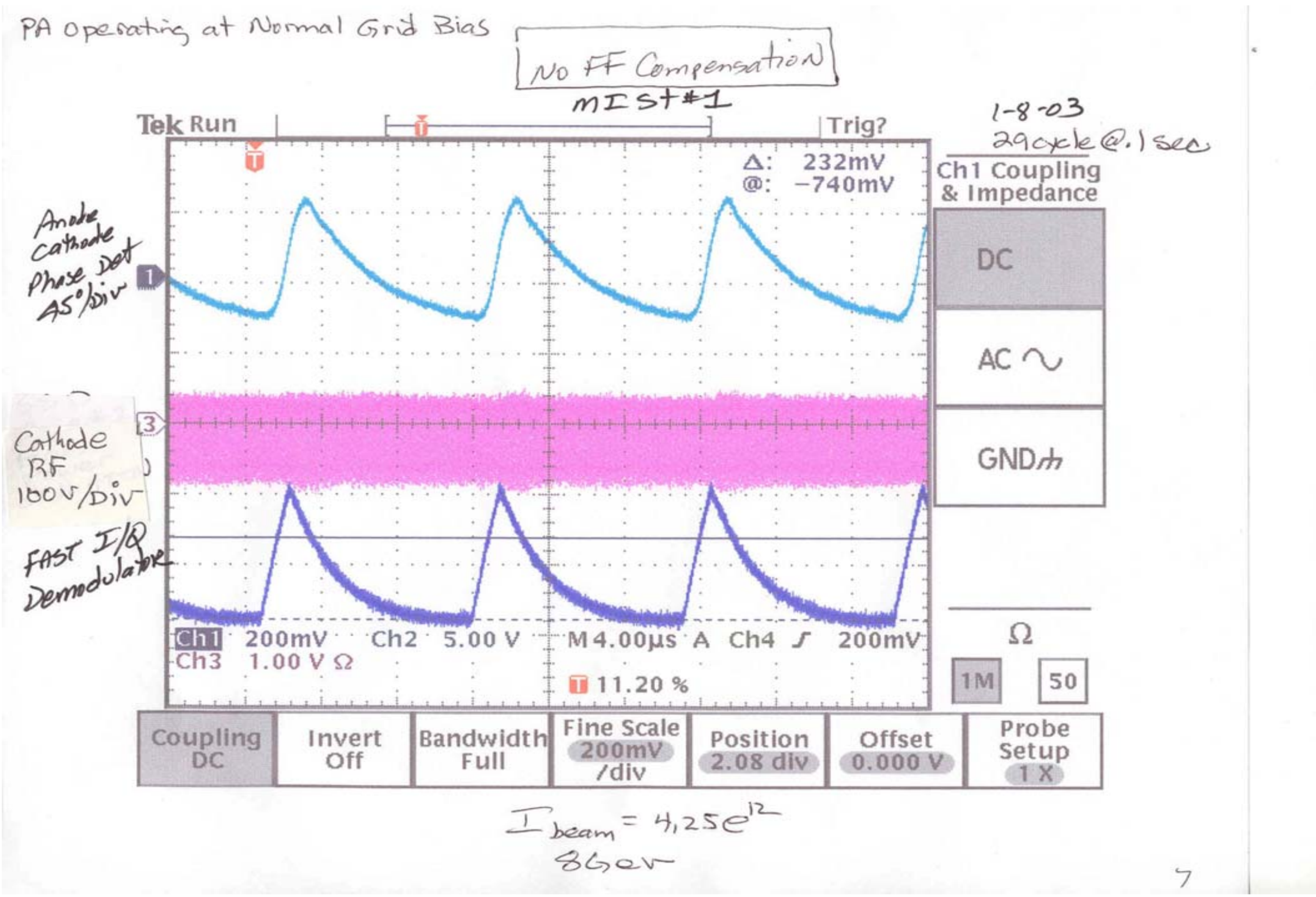
Simulated cavity voltage response to a triangular current pulse for various system conditions.



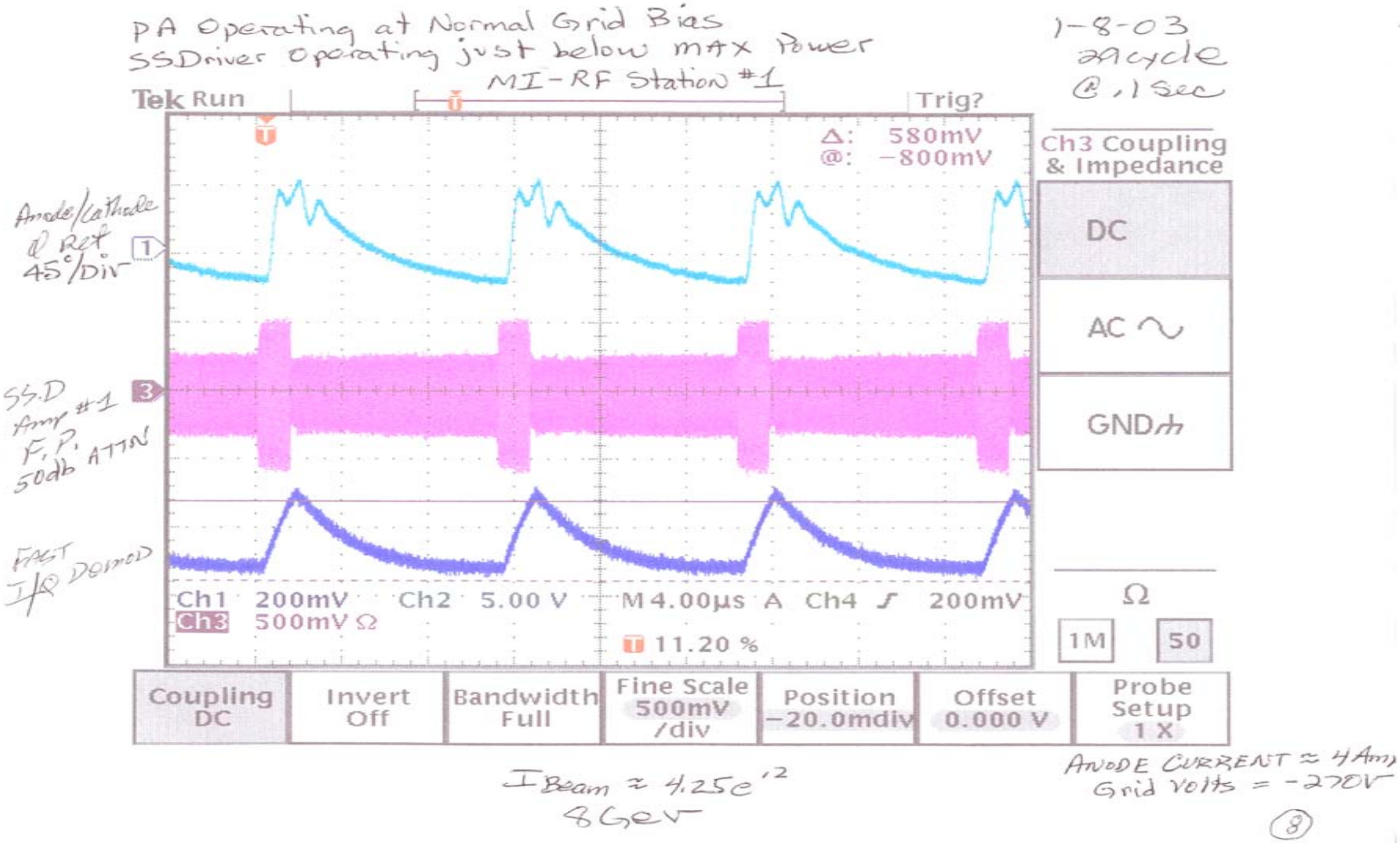
Time domain pictures of beam loading compensation on one rf station



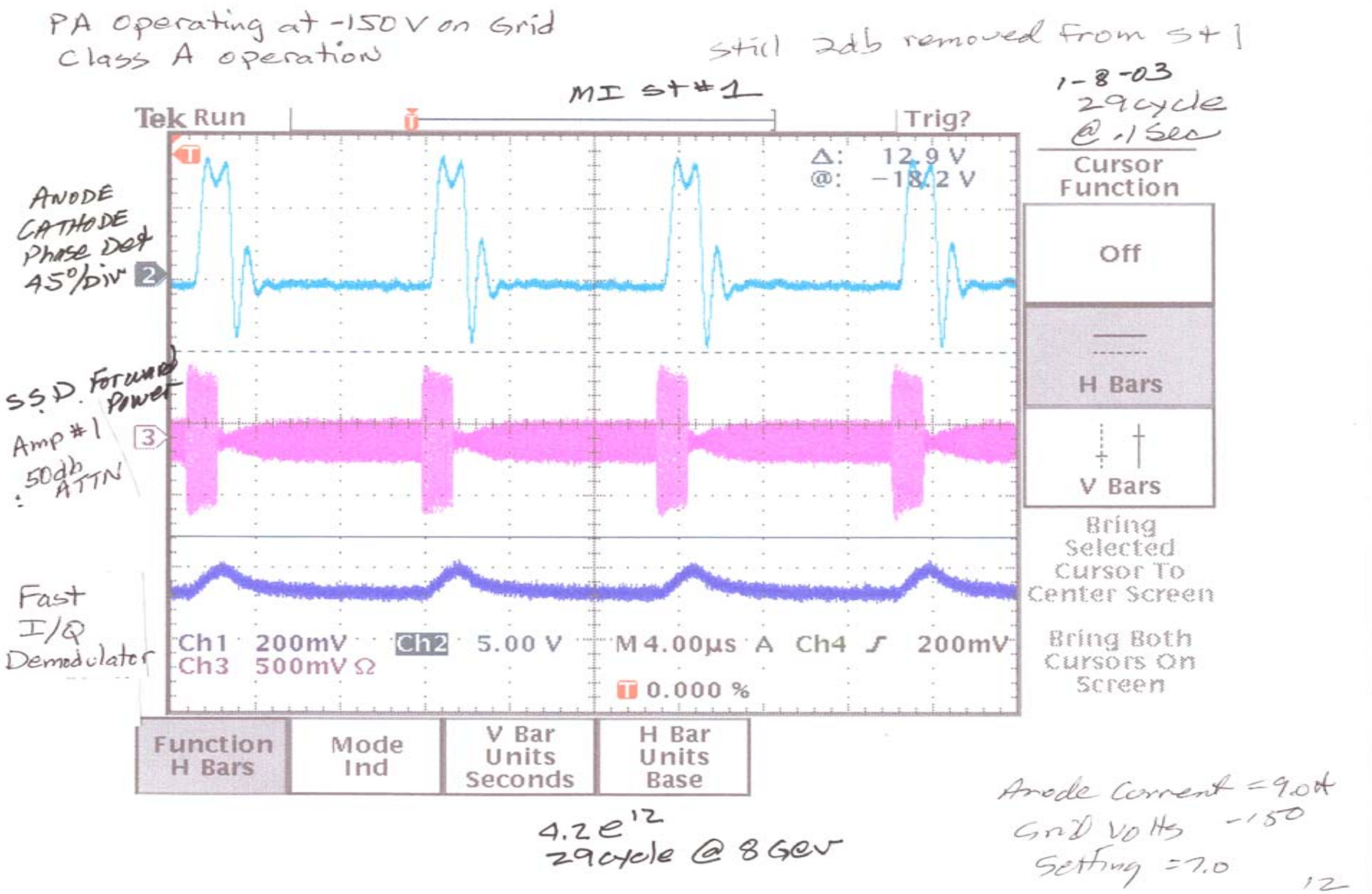
Time Domain Signals of rf station 1 with Normal Bias (Class C) and no FF Compensation.



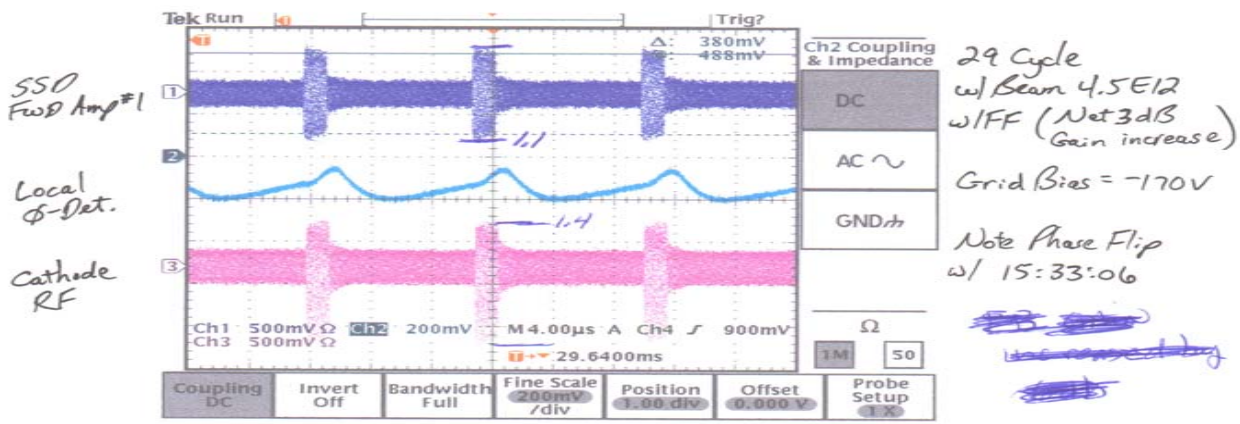
Time Domain Signals of rf station 1 with Regular Bias (Class C) and FF Compensation On.



Time Domain signals for rf station 1 with Class A Bias and FF Compensation On



Cathode rf, forward power and local phase detector for station 1 with 4.8E12 particles and beam loading compensation on.



Cathode rf = $1.4 \times 191 = 267.4\ V_{p.p} = 94.5\ V_{rms}$

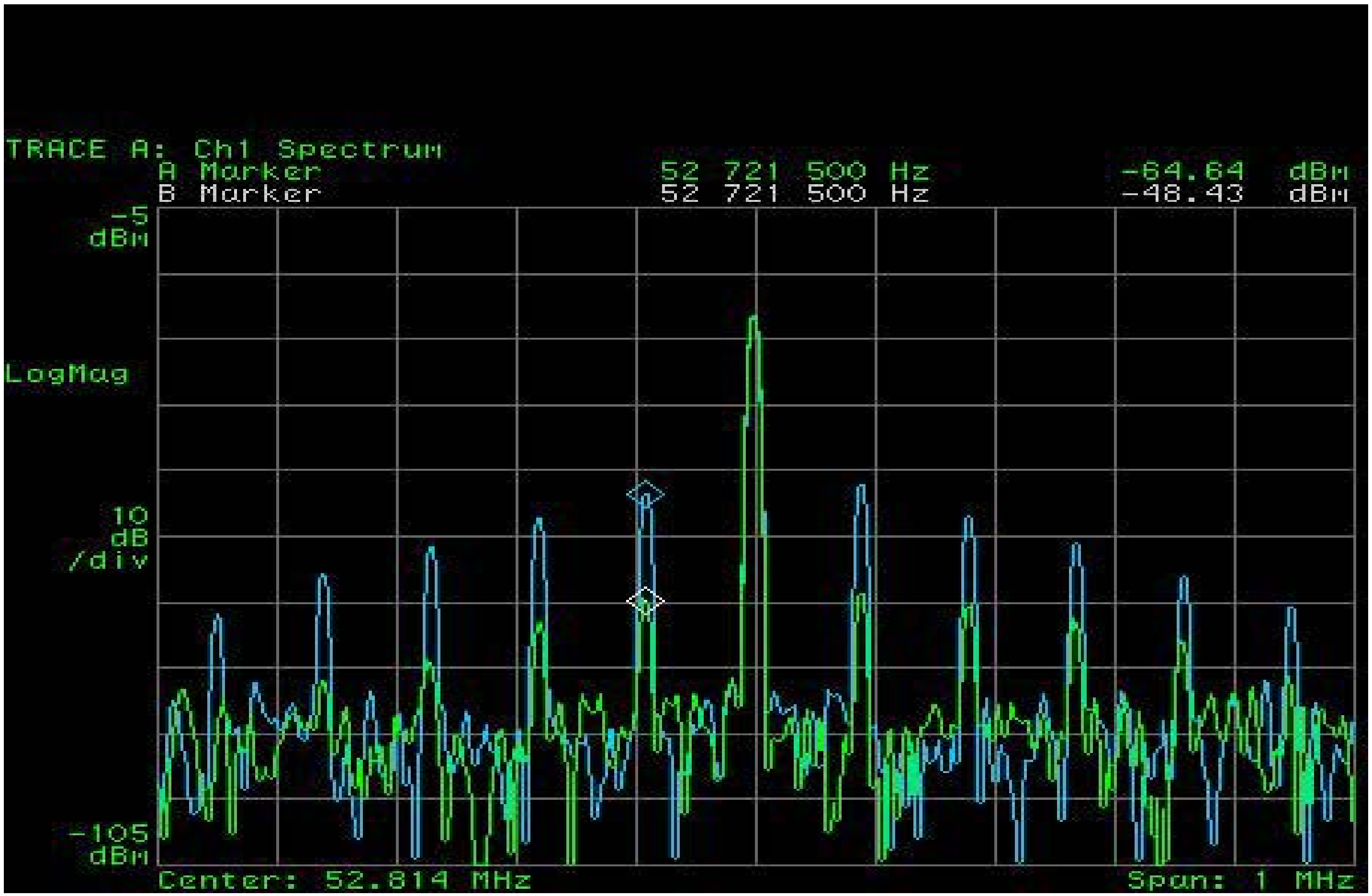
F.P = $1.1 \times 316 = 302$ WATTS $\times 4 = 1208$ watts

$$Z = \frac{V^2}{P} = \frac{(94.5)^2}{1208} = 7.39\,\Omega$$

$$I = \frac{V}{Z} = \frac{94.5}{7.39} = 12.78 \text{ Amps}$$

19

Frequency Domain Pictures of Beam Loading Compensation



Other Beam Dynamics Issues

- Booster bunch rotations
  - Beam in the Booster has to be rotated in the longitudinal phase space before extraction in order to match the low voltage (62KV) buckets in MI
  - Booster longitudinal mode dampers have to work at the highest intensities
- Transition crossing in MI
  - Transition crossing in MI is expected to blow-up the longitudinal emittance of the bunches by 30-35%.
- Longitudinal Instabilities
  - Couple bunch instabilities can dilute the longitudinal emittance of the bunches and affect the bunch rotation at 120 GeV needed to reduce the final bunch length at the target.
  - A bunch by bunch longitudinal dampers is expected to be operational by the end of this year.
- Transverse instabilities
  - Bunch by bunch horizontal and vertical dampers are being commissioned.

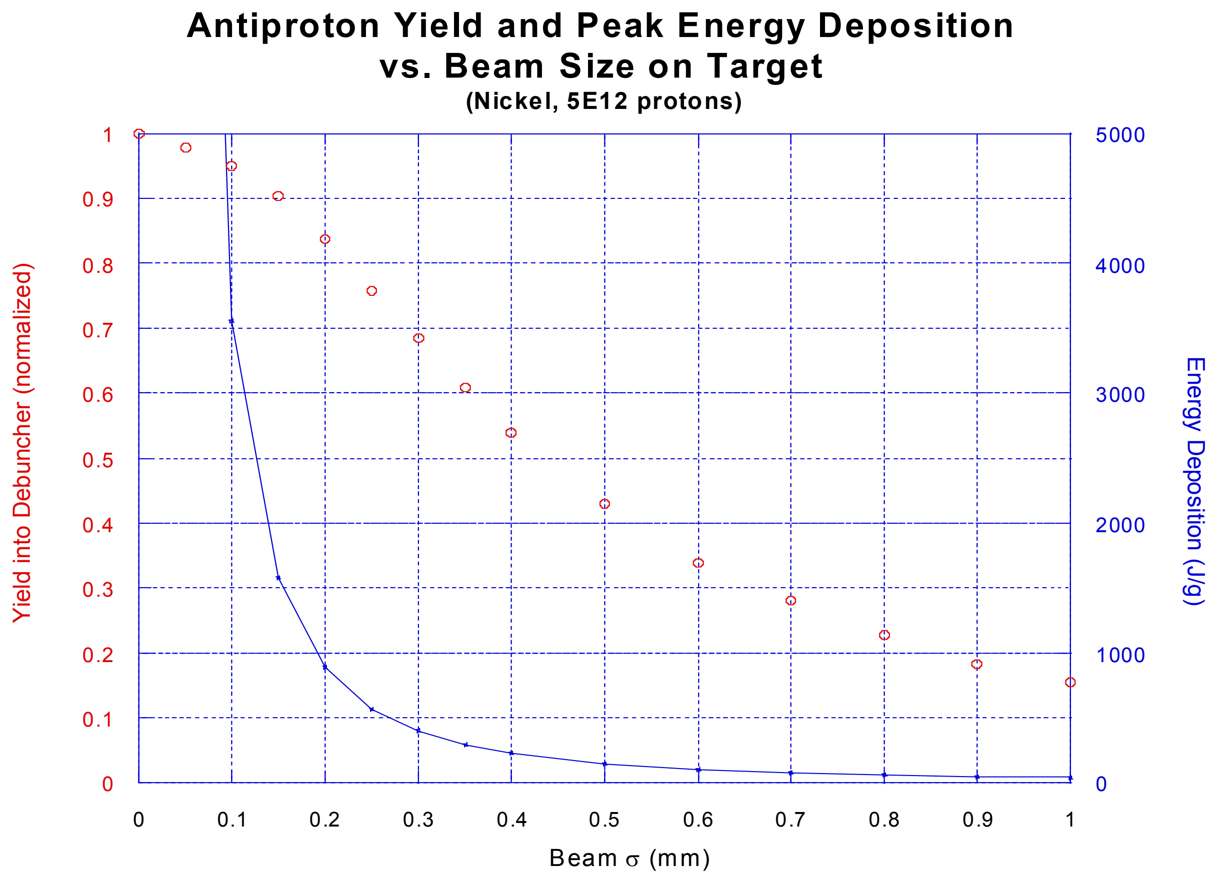
Pbar Target Energy Deposition and Beam Sweeping

- The antiproton production target should be able to take full advantage of the increased proton intensity.
  - No reduction in antiproton yield.
  - Prevent local melting and target damage.
  - Maintain a beam spot size at the target of 0.1mm with larger transverse emittances.
- New target materials with same yield characteristics as the present target but better tolerances have been investigated.
- A beam sweeping system that moves the targeted beam during the 1.6 μsec beam pulse has been constructed.
- Plan to develop beam-line lattice changes that will reduce the beta functions at the target so that σ=0.1 mm in both planes with proton emittances up to 25 pi-mm-mrad.

Pbar Target Energy Deposition and Beam Sweeping (2)

- Inconel 600,625,686, X-750 and Stainless Steel 304 have been tested with beam and compared with Nickel 200. Based on the yield characteristics and resistance to damage Inconel 600 has been identified as the operational target material.
- The upstream target sweeping magnets have been installed in the tunnel and are ready to be tested. The downstream sweeping magnet is being completed and expected to be installed when the testing of the upstream magnets is finished.
- Recent beamline optics improvements have zeroed the dispersion at the target and reduced the spot size to σ_x=0.15mm and σ_y=0.16mm with transverse emittances of 19 pi-mm-mr.
- To achieve the goal of $\sigma_x = \sigma_y$ =0.1 mm with a 25 pi-mm-mrad beam the beta functions at the target will need to be reduced an additional factor of two. New optics solutions will be modeled and tested with beam during the second half of 2003 to identify possible aperture problems.

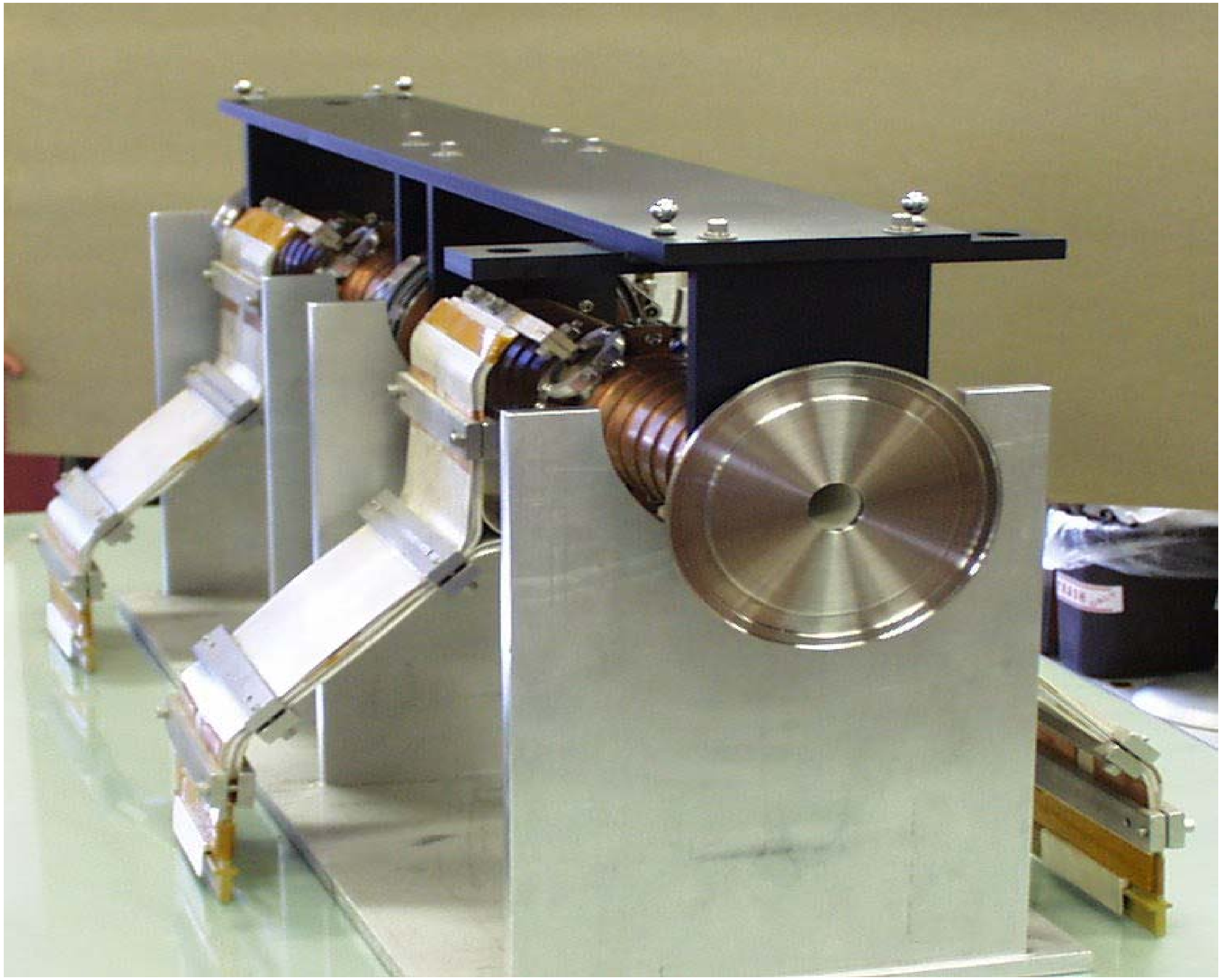
Antiproton Yield and Peak Energy Deposition vs. Beam Size on Target (from MARS model)



Target Reduction yield studies for different materials

Material	Spot size	Starting Yield	Ending Yield	Protons on target	Yield reduction scaled to 10^{18} protons
Nickel 200	$\sigma_{xy} = 0.15, 0.16$	1.000	0.970	5.7×10^{17}	5.3%
Nickel 200	$\sigma_{xy} = 0.22, 0.16$	0.990	0.935	6.6×10^{17}	8.3%
Inconel® 600	$\sigma_{xy} = 0.15, 0.16$	0.995	0.970	10.6×10^{17}	2.4%
Inconel® 600	$\sigma_{xy} = 0.22, 0.16$	0.990	0.960	10.7×10^{17}	2.8%
Inconel® 625	$\sigma_{xy} = 0.22, 0.16$	0.980	0.970	6.6×10^{17}	1.5%
Inconel® X-750	$\sigma_{xy} = 0.15, 0.16$	0.985	0.965	5.7×10^{17}	3.5%
Inconel® 686	$\sigma_{xy} = 0.15, 0.16$	0.970	0.935	1.0×10^{17}	38.2%
Stainless 304	$\sigma_{xy} = 0.15, 0.16$	1.000	0.965	6.1×10^{17}	5.8%

Beam Sweeping Magnet



Studies and Plans

- Study the Booster bunch rotations at high intensities.
- Further optimize the slip stacking curves and reduce the slip stacking cycle time.
- Slip stacked few bunches (7-9) at the highest per bunch intensity and accelerate through transition in MI.
- Continue the beam loading measurements and experiments.
- Trying running all rf stations from class C to class A.
- Come up with a plan with the needed modifications for beam loading compensation.
- Continue with the MI multi-batch high intensity studies and the damper commissioning.
- Proceed with the beam sweeping commissioning and the beam optics studies at the target region.

Conclusions

- Most of the tools required for slip stacking have been developed and the process has been demonstrated to work as expected at low beam currents.
- A serious effort is under way in order to understand what is needed to compensate the beam loading in the 53 MHz cavities at large currents.
- Both transverse and longitudinal dampers will be needed during the slip stacking cycles.
- We have identified a new target for antiproton production.
- Beam sweeping magnets are ready for testing with beam.